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用于现场测量深层岩土导热系数的简化方法

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摘　要:为便于工程上实现应用现场测量确定实际介质的物性,采用一种简化的传热分析方法确定深层岩土导热系数。该方法不需要测量钻孔中埋管的具体位置、上升管和下降管之间的距离以及埋管和回填材料的特性等参数,可消除上述参数测量带来的误差。通过现场测量地下埋管回路的加热热流、回路循环水流量以及回路出入口水温度随时间的变化,利用简化分析和最优化估计方法,确定了某工地地下岩土的导热系数,检验证实了该方法的实用性和可靠性。

关　键　词:传热模型;测量;岩土;导热系数

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1　引　言

由于地层深处温度常年维持不变,远高于冬季的室外温度,低于夏季室外温度,地源热泵有效地克服了空气源热泵的温限和技术障碍,大大提高效率。另外,还具有低噪音、占地面积小、无污染物排放、不抽取并破坏地下水、运行及维修费用低廉和寿命长等许多优点[1~2]。目前欧洲和北美正大力发展和推广应用地源热泵技术[3~4],我国也已开始研究和应用该技术[5~8]。

深层地下岩土导热系数是设计地源热泵系统地热换热器的重要参数,通常用现场测量结合参数估计法来确定深层岩土导热系数[9~14]。目前测试应用的地热换热器与周围岩土换热模型一般较为复杂,需要确定的参数较多,导致出现误差的可能性增大,非常不利于工程上推广应用。已有模型在确定钻孔内热阻时,一般都需要较为详细确定钻孔内埋管的布置与几何尺寸、导热系数以及回填材料的导热系数等。鉴于测量的困难和钻孔内埋管埋设的不确定性,这些参数的误差均较大,从而影响最终物性结果的可靠性。本文尝试提出一个简化的传热模型用于现场测量并确定深层岩土的导热系数。拟采用将钻孔内的总热阻作为一个变量,不计钻孔内具体状况的简化模型。避免确定钻孔中埋管的具体位置、上升管和下降管之间的距离以及埋管和回填材料的物性等参数。理论上讲这样的模型十分粗糙,但是因减少测量参数带来的误差,应用于工程时得到的结果反而可能会更好。

2　简化模型与思路

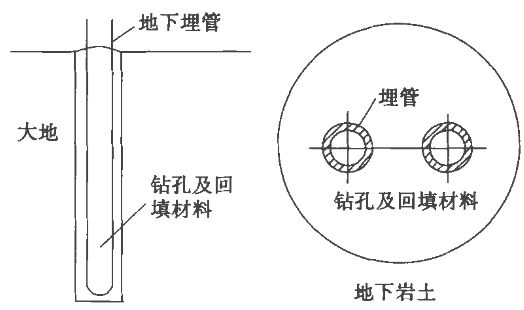

图1　地热换热器结构示意图
(左为立面图,右为横断面图)

地热换热器(一个回路)的结构如图1。为简化分析,引进如下假设:(1)钻孔周围岩土是均匀(设计所需是平均参数);(2)埋管与周围岩土的换热可认为是钻孔中心的一根线热源与周围岩土进行换热,沿长度方向传热量忽略不计(孔径较小,一般约0.1 m,钻孔长度则大于50 m);(3)

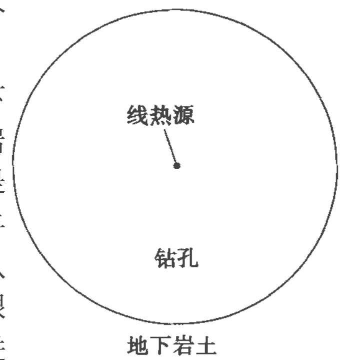

图2　简化的钻孔横断面示意图

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埋管与周围岩土的换热强度维持不变(可以通过控制加热功率完成)。简化后的物理模型如图 2 所示。

根据上述假设，由地热换热器与其周围岩土换热的换热方程可确定管内流体平均温度与深层土壤的初始温度(也是假设的无穷远处的土壤温度)之间的关系为[10~11]：

$$T_f = T_{ff} + q_l \cdot \left[R_0 + \frac{1}{4\pi k_s} \cdot Ei\left(\frac{d_b^2 \rho_s c_s}{16 k_s \tau} \right) \right] \quad (1)$$

其中：$Ei(x) = \int_x^{\infty} \frac{e^{-s}}{S} \mathrm{d}S$，为指数积分函数。

d_b— 钻孔直径，m；

c_s— 岩土的比热，W · s/(kg · ℃)；

k_s— 周围岩土的导热系数，W/(m · ℃)；

q_l— 单位长度线热源热流强度，W/m；

R_0— 单位长度钻孔内的总热阻，℃ · m/W；

T_f— 埋管内流体平均温度，℃；

T_{ff}— 无穷远处土壤温度，℃；

ρ_s— 岩土的密度，kg/m^3；

τ— 时间，s。

上式中的未知参数有：k_s、R_0、c_s、ρ_s。视 $\rho_s c_s$ 作为一个未知数，以其为自变量对 T_f 求偏导数得：

$$\frac{\partial T_f}{\partial(\rho_s c_s)} = \frac{1}{4\pi k_s} \frac{\partial}{\partial(\rho_s c_s)} \left[Ei\left(\frac{d_b^2 \rho_s c_s}{16 k_s \tau} \right) \right] = -\frac{1}{4\pi k_s} \frac{\exp\left(-\frac{d_b^2 \rho_s c_s}{16 k_s \tau} \right)}{\rho_s c_s} \quad (2)$$

式中，岩土的 $\rho_s c_s$ 量级为 10^6，d_b 的量级为 10^{-1}，k_s 的量级为 1，当 τ 比较大时(约数小时)，分子约为 1，而分母量级为 10^6。显然 $\rho_s c_s$ 的变化对 T_f 的影响可以忽略不计。通过同样的分析可知 R_0 和 k_s 的影响则不能忽略。

利用传热反问题求解结合最优化方法同时确定 R_0 和 k_s，求解时估算 $\rho_s c_s$ 近似值(如 200 000 W · s/(m^3 · ℃))。由于求解对其不敏感，无须迭代修改估算值的偏差，这样该问题就变为 R_0 和 k_s 双参数估计问题。

3　测量装置和测量方法

测量装置内部主要结构如图 3，现场测量装置与地热换热器一个回路联接示意图见图 4。测量仪器主要部件由加热器、循环水泵、温度测量装置、流量测量装置、信号变送装置、微机控制与处理装置等构成。测量仪中的管路与地热换热器地下回路相接，循环水泵驱动流体在回路中循环流动，流体经过加热器加热后流经地下回路与地下岩土进行换热。测得的出、入口流体温度、流体流量、加热功率等经信号变送传至微机。

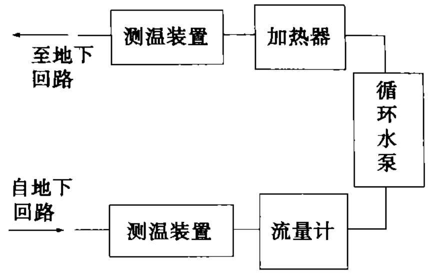

图 3　测量仪内部结构简图

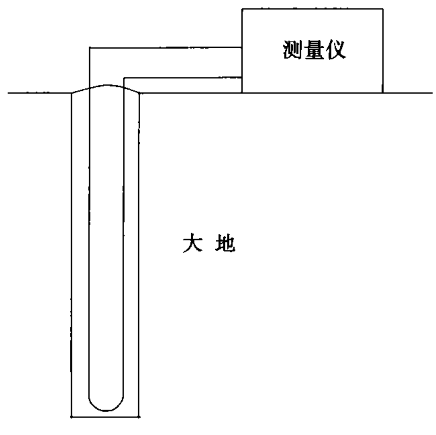

图 4　测量仪安装示意图

在已钻好的钻孔中埋设埋管并按设计要求回填(最好按照将要设计的地热换热器要求埋设，该钻孔中的埋管将来可以作为地热换热器的一个支路使用)，回流充满水循环流动，自某一时刻起对水加热一定时间(数十小时)。测量回路中水的温度及其所对应的时间，根据已知的数据反推钻孔周围岩土的导热系数 k_s 和钻孔内热阻 R_0。将通过传热模型得到的流体平均温度与实际测量的结果进行对比，通过调整传热模型中周围岩土的导热系数和钻孔内热阻，当计算得到的结果与实测的结果误差最小时，对应的导热系数数值即是所求的结果。方差和为：

$$f = \sum_{i=1}^{N} (T_{\mathrm{cal},i} - T_{\mathrm{exp},i}) \quad (3)$$

式中：$T_{\mathrm{cal},i}$— 第 i 时刻由传热模型计算出的埋管中流体的平均温度，℃；

$T_{\mathrm{exp},i}$— 第 i 时刻实际测量的埋管中流体平均温度(近似取出口和入口流体温度的平均值)，℃；

N— 实验测量数据的组数。

方差和 f 的最小值可以通过最优化技术求得，

计算程序流程图见图 5。

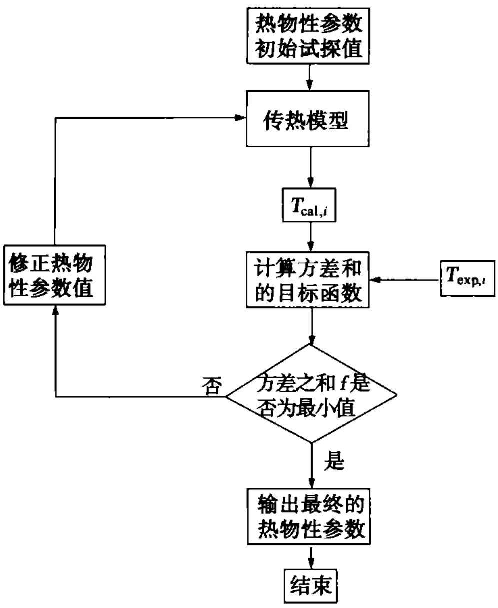

图 5 计算程序流程图

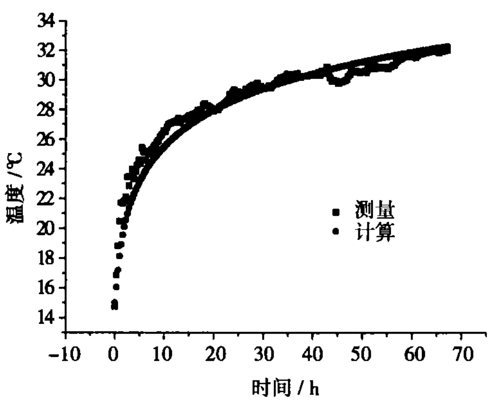

图 6 计算结果与测量结果的比较

4 现场测量实例与结果讨论

在上述讨论的基础上，利用自行研制的深层岩土热物性测量仪对山东建筑工程学院学术报告厅地源热泵空调系统的地下岩土导热系数进行了现场测量。钻孔孔径 115 mm，地下岩土初始温度 14.5 ℃，加热功率 46 W/m。测得的地下埋管出入口流体平均温度随时间的变化如图 6 曲线—Measured 所示，测量时间 68 h。根据测量的数据，计算得到的地下深层岩土的导热系数和钻孔内热阻数值见表 1 和表 2（计算时舍去前 10 h 的数据以满足钻孔内为稳态传热的假设）。可以看出对于不同的试探值，最后计算出的数值稳定性比较好。取导热系数 $k_s = 1.28$ W/(m·℃)，每米钻孔长度钻孔内热阻 $R_0 = 0.064$ ℃·m/W 代入传热模型计算出的地热换热器出入口平均水温随时间变化标绘在图 6 中（曲线—Calculated）。对比实测结果，二者吻合很好。数值计算结果与测量值之间的拟合优度 R^2 为：

$$R^2 = \sum_{i=1}^{N} T_{cal,i}^2 / \sum_{i=1}^{N} T_{exp,i}^2 = 1.0085 \quad (4)$$

说明简化传热模型用于现场测量深层岩土导热系数是可行的。

表 1 k_s 计算结果

试探值 k_s/W·(m·℃)$^{-1}$	试探值 R_0/℃·(m·W)$^{-1}$ 0.02	0.04	0.08	0.12
1.0	1.279 55	1.279 55	1.279 55	1.279 55
1.2	1.279 56	1.279 55	1.279 59	1.279 55
1.4	1.279 55	1.279 55	1.279 55	1.279 54
1.6	1.279 55	1.279 54	1.279 55	1.279 55
1.8	1.279 55	1.279 55	1.279 55	1.279 55
2.0	1.279 55	1.279 55	1.279 55	1.279 55

表 2 R_0 计算结果

试探值 k_s/W·(m·℃)$^{-1}$	试探值 R_0/℃·(m·W)$^{-1}$ 0.02	0.04	0.08	0.12
1.0	0.064 5	0.064 5	0.064 5	0.064 5
1.2	0.064 5	0.064 5	0.064 5	0.064 5
1.4	0.064 5	0.064 5	0.064 5	0.064 5
1.6	0.064 5	0.064 5	0.064 5	0.064 5
1.8	0.064 5	0.064 5	0.064 5	0.064 5
2.0	0.064 5	0.064 5	0.064 5	0.064 5

5 结 语

引入了一种可以应用于现场测量深层岩土导热系数的简化传热分析模型，有效地减少了需要确定的参数，如钻孔中埋管的具体位置、上升管和下降管之间的距离以及埋管和回填材料的物性等参数，相应地减少由于测量上述参数带来的测量误差。利用该分析方法进行了实地测量检验，利用所确定的导热系数计算出的回路出入口平均水温随时间变化与实际测量的结果很好地相符合。

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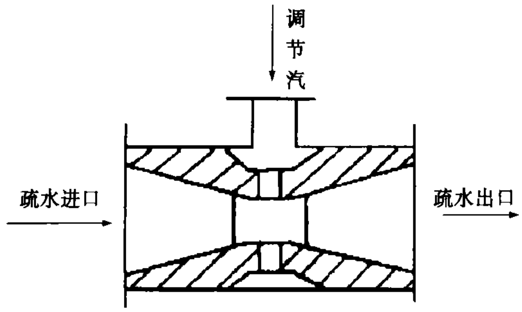

图 1 调节器示意图

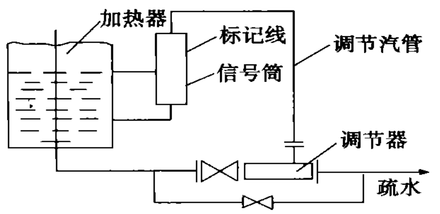

图 2 液位调节器系统图

(3) 部分机组高、低加正常水位的定值不是很科学, 偏低。现各高加水位一般都按照制造厂设计控制水位的零点定, 制造厂规定的控制水位是按静态设计的, 在运行时加热器筒体内实际水位和水位计显示的水位可能并不相同, 由于部分型号的高加结构特点(如 Foster Wheeler 加热器), 疏水在靠近管板的疏水口疏出, 造成疏冷段进口水封处水位最低, 离水封越远, 水位越高; 水位计一般装在水封附近, 而该处蒸汽流速较大, 水位计汽平衡管进口处由于抽吸作用, 使水位计显示水位比筒体内实际水位高; 水封进口易产生涡流, 使得水位虚假升高(约影响 65 mm), 故按静态确定的控制水位偏低, 易破坏水封。要确保水位计指示准确。注意防止出现以下问题: 汽平衡管太长, 保温不好, 蒸汽在其中凝结形成附加水位; 水平衡管堵塞, 阻碍凝结水回流入筒内, 使指示偏高; 水位计联络管安装位置偏高等。

(4) 通过水位调整试验, 确定合理的运行水位。由于部分机组的水位定值就不是很科学, 建议进行水位调整试验, 确定合理的运行水位。试验很方便, 工况稳定后, 保持各参数不变, 逐步提高高加水位, 观察疏水温度下降情况, 当水位提高到疏水温度不再降低的时候, 说明此时已无蒸汽进入水封, 然后再考虑适当裕量即为最低水位值, 而高水位则以不淹没排空气管为限。

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[刊，汉] / SHEN Xiang-zhi，YAN Jian-hua（Research Institute of Thermal Energy Engineering under the Zhejiang University，Hangzhou，China，Post Code：310027），LU Tai（Power Engineering Department，Northeast Electric Power Institute，Jilin，China，Post Code：132012）//Journal of Engineering for Thermal Energy & Power. — 2003，18(5). —497～500

On the basis of experimental research a method for designing J-shaped refeed valve was developed from the perspective of structural dimensions，air-charging pressure and quantity. Some engineering calculation examples are given，which can serve as reference data during the design of circulating fluidized bed boilers. **Key words**：circulating fluidized bed boiler，J-shaped refeed valve，design method

单级叶片倾角对百叶窗浓缩器分离特性影响的工业试验＝**Industrial Tests For Clarifying the Impact of Single-stage Blade Dip Angle on the Separation Characteristics of a Louver Concentrating Device** [刊，汉] / YANG Long-bin，LI Zheng-qi，CHEN Li-zhe，et al（College of Energy Science & Engineering under the Harbin Institute of Technology，Harbin，China，Post Code：150001）//Journal of Engineering for Thermal Energy & Power. — 2003，18(5). —501～503

On a 670 t/h bituminous coal-fired boiler equipped with a race pulverizer-baseddirect-fired pulverized-coal preparation system，single-stage blade and gas-solid two-phase tests were conducted to determine the separation characteristics of a louver concentrating device. It is found that with the dip angle of a single-stage movable blade set at 32° the share of fuel-rich primary air is relatively low，the separation and concentrating efficiency are relatively high. Meanwhile，the comprehensive resistance loss factor and pressure loss is respectively 0.92 and 471 Pa. **Key words**：boiler，concentrating device，louver，gas-solid flow

油田直热炉温度/流量的模糊控制＝ **Fuzzy Control of the Temperature and Flow Rate of an Oil Field Direct-heated Furnace** [刊，汉] PANG Li-ping，WANG Jun（Department of Flight Vehicle Design and Applied Mechanics，Beijing University of Astronautics and Aeronautics，Beijing，China，100083）//Journal of Engineering for Thermal Energy & Power. — 2003，18(5). —504～506

The improper control of a direct-heated furnace installed at an oil field will give rise to bias-flows during its combustion，often resulting in coke formation in the heating tubes，which eventually have to be replaced. On the basis of analyzing the underlying causes of bias flows during the operation of the direct-heated furnace and possible measures for dealing with such flows a fuzzy control scheme for the temperature and flow rate has been proposed for the furnace. The implementation of the scheme has thoroughly solved the problem of bias-flows，eliminating the need for replacement of the heating tubes. Moreover，the use of a discrete fuzzy controller proposed by the authors can also solve the bias-flow problems in other control systems involving the distribution of fluids，**Key words**：fuzzy control，uniformity control，direct-heated furnace，bias flow

电厂负荷调度的智能决策方法＝**Intelligent Decision-making Methods for Load Dispatching in Power Plants** [刊，汉] / YU Guo-qiang，LU Jian-hong（Department of Power Engineering，Southeastern University，Nanjing，China，Post Code：210096），GONG Cheng（Tiansheng Harbor Power Generation Co. Ltd.，Nantong，Jiangsu Province，China，Post Code：226000）//Journal of Engineering for Thermal Energy & Power. — 2003，18(5). —507～511

Iso-micro increase approach and dynamic planning are two methods of optimized dispatching of power plant loads currently in common use. After a comparison of the above two methods the authors have pointed out their defects in the actual dispatching of plant loads. On this basis an intelligent decision-making strategy is proposed to reduce the cost of power generation，taking advantage of the actual experience gained in load dispatching. With respect to four units of 125MW plant installed at Tiansheng Harbor Power Generation Co. Ltd in Nantong City an optimized load dispatching system was developed，based on load intelligent decision-making strategy. **Key words**：load dispatching，iso-micro increase method，dynamic planning method，intelligent decision-making strategy，rules base

用于现场测量深层岩土导热系数的简化方法＝**A Simplified Method for On-site Measurement of the Thermal**

Conductivity of Deep-layer Rock Soil [刊, 汉] / YU Ming-zhi, PENG Xiao-feng (Thermal Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084), FANG Zhao-hong (Shandong Institute of Architectural Engineering, Jinan, China, Post Code: 250014) //Journal of Engineering for Thermal Energy &Power. — 2003, 18(5). —512 ~514, 518

To facilitate the on-site measurement of physical properties of media in engineering applications, a simplified heat-transfer analytical method is proposed to determine the thermal conductivity of deep-layer rock soil. The method under discussion does not need exact information about the following parameters: the specific location of an embedded tube in a borehole, the distance between a riser tube and a downcomer, and the physical properties of the embedded tube and backfill material, etc. As a result, all errors brought about by the measurement of the above parameters can be eliminated. An on-site measurement was taken of the heat flux of an embedded tube loop, the loop circulating water flow rate and the time-dependent change of inlet and outlet water temperature of the loop. On this basis and by utilizing a simplified analytical and optimized evaluation method the thermal conductivity of underground rock soil on a certain working site was determined, thus verifying and confirming the practicality and reliability of the recommended method. **Key words**: heat transfer model, measurement, rock soil, thermal conductivity

高、低压加热器低水位运行的分析研究= **Analytical Research on the Low Water-level Operation of High and Low Pressure Heaters** [刊, 汉] / SUN He-tai (Steam Turbine Department, Jiangsu Provincial Research Academy of Electric Power, Nanjing, China, Post Code: 210032) //Journal of Engineering for Thermal Energy &Power. — 2003, 18(5). —515 ~518

The harmful effects of low water-level operation of high and low-pressure heaters are presented and discussed. By using an equivalent enthalpy-drop method a thermo-economic analysis was performed of 125MW and 200MW units involving low-pressure heaters operating at a low water level with the extent of negative influence being evaluated. From the viewpoint of structural design and on-site operating conditions, etc the causes leading to heaters operating at a low and even an absence of water level are identified with some measures for improvement being proposed. All the above may have a significant practical value for the guidance of power plant operation. **Key words**: heater, water level, economy, equivalent enthalpy-drop method

CC12 MW 供热汽轮发电机组热力系统简化设计及应用= **Simplified Design of a Thermodynamic System for a CC12 MW Heat-supply Turbogenerator and its Implementation** [刊, 汉] / JIN Bao-hua, CAO Yu (Power Generation Department, Liaoning Electric Power Exploration and Design Institution, Shenyang, China, Post Code: 110005), QIN Yan (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy &Power. — 2003, 18(5). —519 ~522

The simplified design philosophy and technical features of a CC12MW turbogenerator thermodynamic system for heat supply are described. Moreover, the economic benefits and operating conditions after the simplification of the thermodynamic system are also presented with an analysis of the still existing problems and relevant measures taken for their resolution. **Key words**: thermodynamic system, simplification, thermal load, rotating-film deaerator

能量分析与一次风煤粉浓度测量= **Energy Analysis and Measurement of Pulverized-Coal Concentration in Primary Air** [刊, 汉] / YIN Jing, YANG Xing-sen (Thermal Energy Research Institute under the Shandong Provincial Electric Power Academy, Jinan, China, Post Code: 250002) //Journal of Engineering for Thermal Energy &Power. — 2003, 18(5). —523 ~525

During the boiler operation of a thermal power plant the uniformity of pulverized-coal flow of a pulverized-coal burner in primary air plays a key role in ensuring the safe and economic operation of a boiler. The accurate measurement of the concentration of pulverized coal in primary air is a problem of great importance, which has yet to be effectively solved. This is especially so in the case of pulverized coal monitoring in a boiler using exhaust gas for pulverized-coal transport. The mixed process of primary-air flow and pulverized coal particles is analyzed. On this basis and proceeding from the en-